Compact LTCC Balun using L-C Embraced Structure for 128 MHz 3T MRI Applications

Qiang MA, Huanyan TIE, Bo ZHOU

Dept. of College of Electronic and Optical Engineering, Nanjing University of Posts and Telecommunications, Nanjing, 210023, People's Republic of China

sarahxboy@hotmail.com

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Abstract. *A compact lumped-element balun is proposed for 128 MHz frequency 3 Tesla (T) magnetic resonance imaging (MRI) applications. The proposed L-C embraced structure places vertically-interdigital-capacitor (VIC) inside spiral inductor, thus three L-C elements only take up one inductor's area. Therefore, significant size reduction and integration increment are both achieved without increasing the number of substrate layers. The balun is built on a 10-layer thickness low temperature co-fired ceramic (LTCC) substrate and has the smallest reported size of only 0.007 × 0.008 × 0.0009* λ_g. *Moreover, the proposed balun also has a 2nd-order harmonic suppression of 32 dB. Furthermore, comparisons and discussions are also implemented.*

Keywords

Compact, balun, low temperature co-fired ceramic (LTCC), MRI

1. Introduction

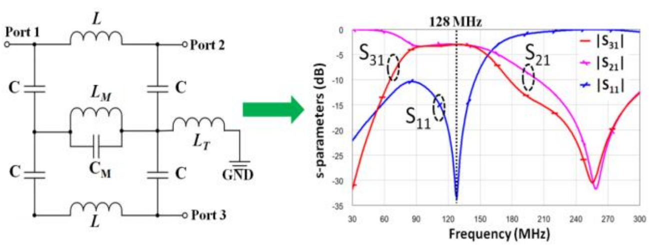
3 Tesla (T) magnetic resonance imaging (MRI) scanner working at 128 MHz frequency is a vital medical diagnostic equipment that offers a non-invasive method of imaging with a high sensitivity [1–7]. Balun plays an important role in MRI scanner, which is used to implement signal conversion between balanced and unbalanced signals with the same magnitude but 180° phase difference. Miniaturization of the balun is a big challenge since the working frequency is only 128 MHz, which falls in the very high frequency (VHF) band. Active baluns using nonlinear components provide smaller size but poor linearity [8]. Integrated passive device (IPD) technology can achieve compact size but poor capability of handling high power signals [9], [10]. Magnetic coil and ferrite core made baluns are dominated in the commercial VHF band applications due to the small size and low cost, but they are not suitable for the MRI applications, because the strong static magnetic field of MRI may have interferences with magnetic and ferrite cores. Passive balun using planar layout is linear but takes up a large size especially at VHF band. Vertical integration using low temperature co-fired ceramic (LTCC) and Liquid Crystal Polymer (LCP) technologies have been reported for miniaturization of passive components. However, the multilayered vertically-interdigital-capacitors (VICs) and spiral inductors have no further enhancement of capacitance/inductance and improvement of miniaturization [11–14]. Although inductor and capacitor (L-C) stacked resonator has been reported for circuit miniaturization, it increases both the number of LTCC layers and fabrication cost [15]. Therefore, further miniaturization of lumped capacitor, inductor and L-C constructed resonator is worth investigating.

In this paper, a miniaturized lumped-element 10-layer LTCC balun with size reduced L-C embraced structure is proposed for 128 MHz frequency 3T MRI applications. Placing VIC inside a spiral inductor is not only practicable with satisfied performances, but also can be used to further minimize the circuit size of L-C constructed structures.

2. Design and Balun Implementation

2.1 Circuit Topology

Since size reduction of the balun is aiming at reducing the size of parallel or series L-C circuit, the first step is to choose a circuit topology with parallel or series L-C element constructed circuits. To start the design at the center frequency of 128 MHz and a 2nd-order harmonic suppression of higher than 30 dB, a well-known circuit model [16]



(a) (b)

Fig. 1. (a) Circuit topology and (b) its corresponding s-parameters.

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with 9 elements is selected, shown in Fig. 1(a). The topology has a bandstop resonator with parallel capacitor (C_M) and inductor (L_M), which create stopband characteristics at high-order harmonic frequency for both through and coupled signals. A tail inductor (L_T) is interconnected with the resonator, which is used to broaden the bandwidth of the balun. The parallel L-C elements (C_M & L_M) and series element (L_T) provide a great possibility for size reduction. The corresponding element values extracted from Microwave Office [17] optimization are: C = 28 pF, C_M = 17 pF, L = 85 nH, L_M = 39 nH and L_T = 17 nH. And the corresponding s-parameters are shown in Fig. 1(b).

2.2 L-C Embraced Structure

Figure 2(a) shows parallel and series L-C part, which is implemented in the proposed L-C embraced structure for size reduction and integration increment. Figure 2(b) presents the geometry of the proposed L-C embraced structure. Figures 2(c) and (d) show the 3D structure of the proposed L-C embraced structure from Port 1 view and Port 2 view, respectively. The outside of the L-C embraced structure is the multilayered spiral inductor (L_M & L_T), and the inner is VIC (C_M). Since the unused space inside the inductor is further and fully utilized, several L-C elements only occupy one inductor's area, which shows size reduction and integration increment. By tuning the number of spiral inductor's turns and the number of VIC's vertical fingers, the inductance and capacitance can be adjusted, respectively. For a compact size, VIC C_M uses 10 fingers with a length of W_{CM} = 1.9 mm to reach 17 pF, shown in Fig. 3. As the Q-factor of inductor has a strong influence on the insertion loss of the balun, multilayered spiral inductors are using a 0.2 mm wide high-impedance line to achieve high inductances and Q-factors. Thus, inductor L_M use 4.5 turns with a length of W_{LM} = 3 mm to reach 39 nH from top layer to Layer 5. Inductor L_T uses 1.75 turns with a length of W_{LT} = 3 mm to reach 20 nH located from Layer 5 to Layer 6. The tail inductor L_T in interconnected to the

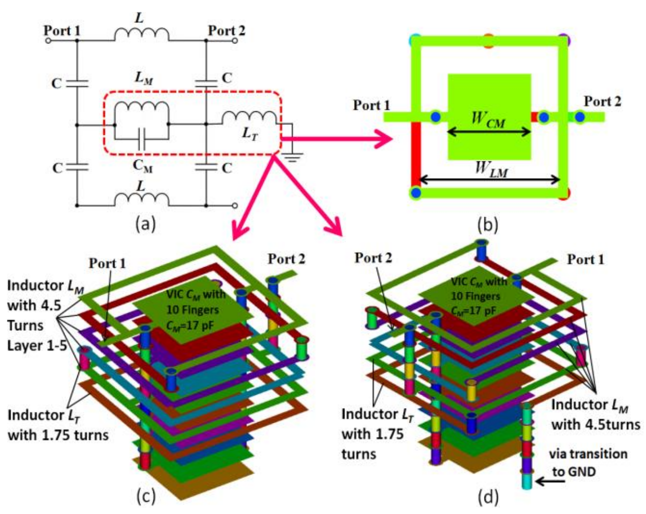

Fig. 2. The proposed L-C embraced structure: (a) L-C embraced elements in topology, (b) planar geometry, (c) 3D view from Port 1 and (d) 3D view from Port 2.

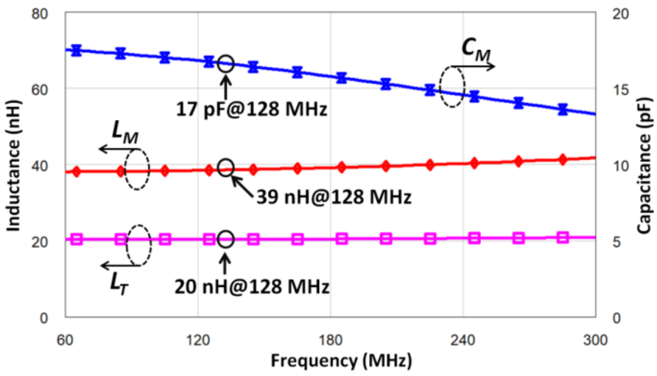

Fig. 3. EM-simulated capacitance of C_M and inductance of L_M, L_T.

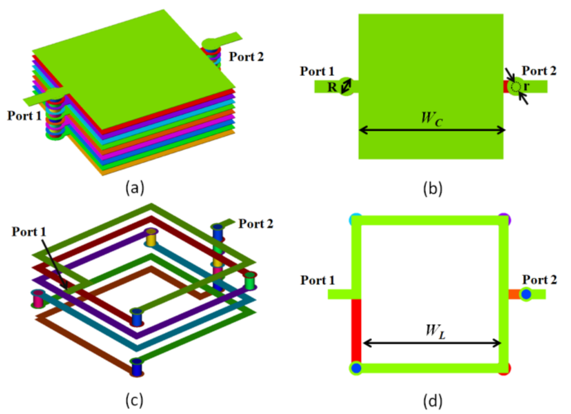

Fig. 4. (a) 3D view of C, (b) top geometry of C, (c) 3D view of L, (b) top geometry of L.

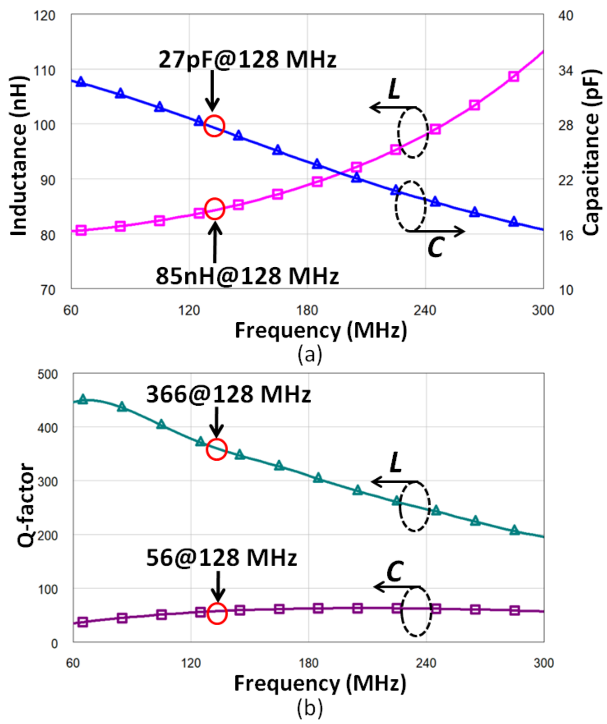

Fig. 5. EM-simulated results: (a) Inductance of L and capacitance of C, (b) Q-factor of L and C.

ground by via transition from Layer 6 to the bottom ground, shown in Fig. 2(d).

2.3 VIC C and Inductor L Design

The 3D and top geometry of the VIC C is shown in Fig. 4(a) and (b), respectively. VIC C is built with 10 vertically placed finger pads for a compact size. The fingers are designed in square shapes for less dimension parameters to be optimized. Finally, it reached 27 pF with a Q-factor of 56 at 128 MHz when W_C = 2.5 mm, shown in Fig. 5(a) and (b). The 3D and top geometry of the inductor L is shown in Fig. 4(c) and (d), respectively. Inductor L uses 5.5 turns and a length of W_L = 3 mm to reach 85 nH with a Q-factor of 366 at 128 MHz, shown in Fig. 5(a) and (b). For the sake of symmetrical and aesthetically shaped layout of the balun, elements L, L_M and L_T with different inductances are implemented with the same horizontal geometry size.

2.4 Entire Balun Implementation

The physical layout of the proposed balun can be easily assembled, and a fine tuning of dimension parameters is implemented. Mutual coupling effect between elements is weak and can be ignored as the working frequency is only several dozens of megahertz. Finalizing the entire balun layout is using electromagnetic (EM) simulator AXIEM [18]. The complete balun is assembled in a 10-layer LTCC substrate, shown in Fig. 6. Each LTCC layer has a post-fired thickness of 0.1 mm in Ferro-A6 material with a dielectric constant of 5.9 and loss tangent of 0.002. The final optimal parameters are: W_{CM} = 1.9 mm, W_C = 2.5 mm, W_L = 3 mm, W_{LM} = 3 mm, W_{LT} = 3 mm, r = 0.2 mm and R = 0.3 mm, where the parameters are defined in Fig. 2(b), Fig. 4(b) and (d), respectively. Diameters of all via and via pad in the design are 0.2 and 0.3 mm, respectively. The top geometry and photograph of the proposed balun are shown in Fig. 7(a) and (b), respectively. Inductors L, L_M and L_T have the same horizontal geometry for the symmetrical and aesthetical layout. The size of the proposed balun is only $8.5 \times 9.5 \times 1$ mm, which is equivalent to $0.007 \times 0.008 \times 0.0009\ \lambda_g$, where λ_g is the guided wavelength on a 1-mm thickness (10 layers) Ferro-A6 substrate at 128 MHz.

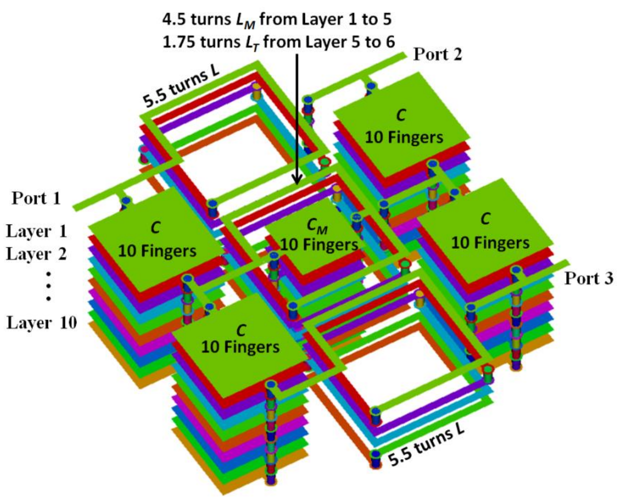

Fig. 6. 3D structure of the proposed balun.

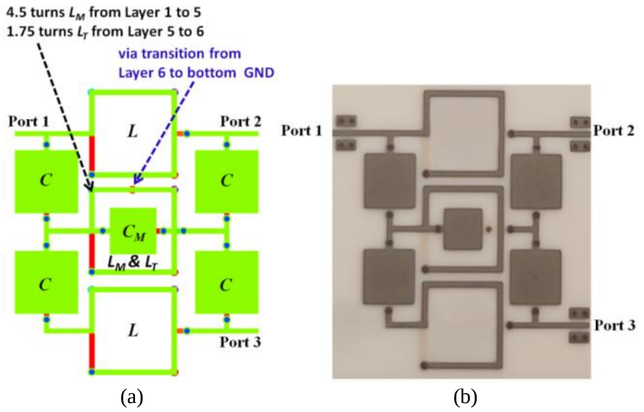

Fig. 7. The proposed balun: (a) Top geometry and (b) photograph. (Bottom ground layer is hidden for a complete 3D view.)

3. Simulation and Measurement

300µm-GSG pads have been reserved at each port for probe measuring, shown in Fig. 7(b). Measurements are carried out by Agilent N5230C network analyzer and Cascade Microtech Summit 9000 probe stations. The simulated results agree well with the measurements as the working frequencies are only several dozens of megahertz. The measured working frequency is from 110 to 140 MHz based on a return loss of 15 dB, shown in Fig. 8. Measured

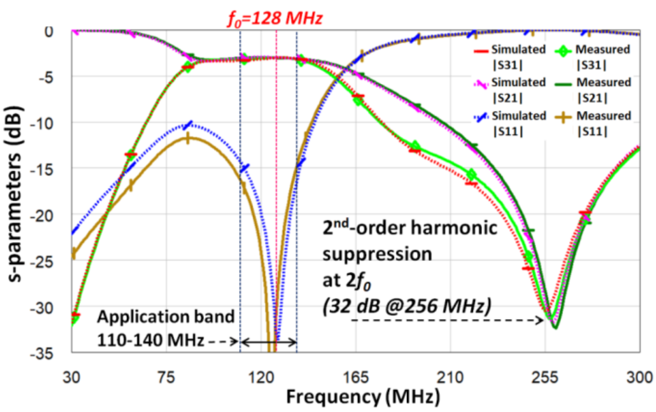

Fig. 8. Simulated and measured s-parameters.

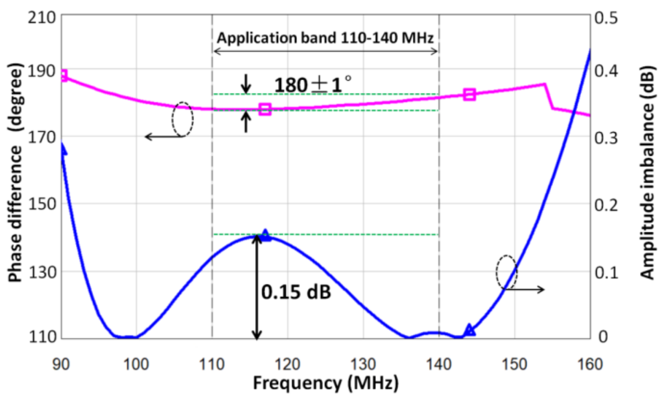

Fig. 9. Measured phase difference between the through and coupled port, and amplitude imbalance.

Ref.	Center frequency (MHz)	Vol. $\times\frac{1}{10^5\lambda_g^3}$	Number of L-C elements	2^{nd}-order harmonic suppression function	Amplitude imbalance	Phase difference	Technique
[9]	4035	1582	8	Yes	0.35 dB	180 ± 5.26°	IPD
[10]	2400	0.1315	6	No	0.5 dB	180 ± 3°	IPD
[11]	2250	0.2752	6	No	1 dB	180 ± 7°	LCP
[12]#	2450	11.06	8	No	1 dB	95 ± 2°	LTCC
[13]	925	0.983	6	No	0.35 dB	180 ± 4°	LTCC
This work	128	0.0006	9	Yes	0.18 dB	180 ± 1°	LTCC

90° coupler,
This work has the largest number of L-C elements, but the smallest size, lowest amplitude imbalance and lowest phase difference.

Tab. 1. Size and performance comparisons.

S_{11}, S_{21} and S_{31} are better than –15, –3.3, –3.2 dB from 110 to 140 MHz, respectively. The proposed balun has a 2^{nd}-order harmonic suppression of 32 dB at 256 MHz for both through and coupled signals. The measured amplitude imbalance is less than 0.15 dB, and the measured phase difference between the through and coupled port is within 180 ± 1° from 110 to 140 MHz, shown in Fig. 9. The tiny dispersion between the simulated and measured results is due to the LTCC material shrinking and surface metal bending after LTCC material co-firing.

4. Comparison and Discussion

Comparisons of size and performance are listed in Tab. 1, which shows the proposed balun has the largest number of L-C elements but the smallest size, lowest amplitude imbalance and lowest phase difference between the through and coupled port among [9–13].

Some design notices about the L-C embraced structure are worth mentioning:

(1) First, the I/O ports of inductor and VIC in the L-C embraced structure have a great flexibility of interconnecting. The number of VIC's fingers (layers) and the turns of spiral inductor (layers) can be different and adjusted according to the required capacitance and inductance.

(2) Secondly, the distance between the inner VIC and outer inductor is recommended to be more than 0.15 mm to minimize the mutual coupling effect between L-C elements. The distance needs to be creased if the working frequency increases.

(3) Third, the outline of spiral inductor and the VIC's pads are encouraged to use round shape to enhance the Q-factor (e.g. in [13]), which is helpful to reduce the insertion loss.

(4) Fourth, the proposed L-C surrounded structure not only can be constructed in an L-C parallel circuit, but also can be used with L-C series circuit for size reduction.

(5) Finally, as most intermedia frequencies (IFs) of super heterodyne receivers are less than 200 MHz and falling in the VHF band, the balun can be used in the IF circuit of super heterodyne receivers as well.

5. Conclusion

A miniaturized lumped-elements LTCC balun is proposed and implemented using L-C embraced structure for 128 MHz 3T MRI applications. The proposed balun has the smallest reported size with only 0.007 × 0.008 × 0.0009 λ_g. The balun also has the lowest amplitude imbalance and lowest phase difference among the compared literatures. The L-C surrounded method can be widely used to minimize the size of both parallel and series L-C circuits, thus further size reduction can be achieved for lumped passive components.

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About the Authors …

Qiang MA is currently working towards the M.S. degree at the College of Electronic and Optical Engineering, Nanjing University of Posts and Telecommunications, Nanjing, People's Republic of China. His research interests include MMIC development.

Huanyan TIE is currently working towards the B.E. degree at the College of Electronic and Optical Engineering, Nanjing University of Posts and Telecommunications, Nanjing, People's Republic of China. Her research interests include microwave integrated circuits development.

Bo ZHOU received the B.S. degree from the Jiangsu University of Science & Technology in 2004, the M.S. degree and Ph.D. degree in Microwave Engineering from Nanjing University of Science & Technology in 2008 and 2014, respectively. He was a Senior Microwave Engineer in Ericsson during 2007-2015. Currently, he is working at Nanjing University of Posts and Telecommunications from 2015. His research interests include microwave circuit design and microwave optimization algorithm research.